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6. AUTHOR(S) Dr Blumenthal					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of California, SB Cheadle Hall Santa Barbara, CA 93106-6150				8. PERFORMING ORGANIZATION REPORT NUMBER	
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# Final Technical Report

## Research Agreement No. FA9620-98-1-0404

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University of California  
Santa Barbara, CA 93106  
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### 1 1.0 Purchased Equipment

The following equipment was purchased in conjunction with industrial matching funds in the form of discounts greater than the standard educational discounts.

#### Vendor/

#### (Qty) Description

#### Cost

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(1) PP10-G pin preamplifier receiver

\$6,680.50

#### SHF Design/

Microwave Amplifier

\$900.00

#### Melles Griot/

(4) Optical Tables and overhead equipment racks

\$48,592.03

(1) Nmax 3-axis micropositioners with piezo feedback

\$20,097.03

#### Hewlett Packard Company/

(1) 8156 Power Meter Mainframe

\$9,842.97

#### Photonetics/

(1) Tunics-PRI-1550 Tunable Laser System

\$26921.34

#### Tektronix/

(1) Rhode and Schwartz 40 GHz RF

\$59,726.65

Spectrum Analyzer

#### Scientific Instrument/

(1) SCD-151A Sony RGB Color CCD Camera

\$3,845.07

#### Uniphase/

(4) Wideband Analog Modulator, 2.5 Gbps

\$16,907.52

#### Westbond/

(1) Die Bond Machine

\$12,976.63

**Total Purchase Cost for all Items**

**\$206,489.74**

## 1.1 Changes to Original Equipment List

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- Four Channel MMIC-based Transmitter Module for RF/Optical Subcarrier Multiplexed Communications
- Optical Network Channel Protection Switching Demonstration using a Bi-Directional Reconfigurable Multichannel Add/Drop Multiplexer

### 2.1 Optically Pre-amplified Receivers using Nonlinear Wavelength Converters

We have demonstrated a novel broadband optically pre-amplified receiver that is capable of detecting any network wavelength using a fixed center frequency narrowband optical filter. We compared this receiver design shown in Figure 1 with the narrow band pre-amplified receiver design and the most general broadband pre-amplified receiver designs shown in Figure 2.

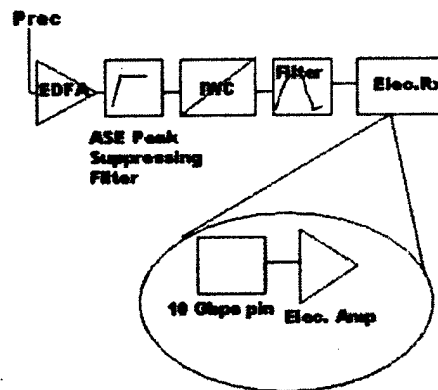


Figure 1. Optical pre-amplified receiver using an interferometric wavelength converter (IWC).

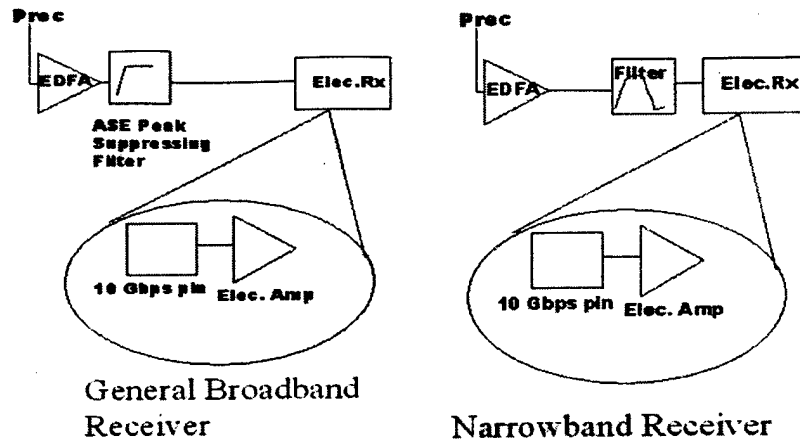


Figure 2: Narrowband pre-amplified receiver and the broadband pre-amplified receiver

In our experiment the incoming wavelength at 1557 nm (in principle could be any of the ITU grid wavelengths) is converted to a local wavelength 1550 nm, using a XPM in a Michelson interferometric configuration. The 0.6 nm bandwidth optical filter filters the original wavelength. The electrical receiver is a Nortel 10 Gbps pin receiver with a SHF 10 GHz amplifier. In each of the three cases the receiver sensitivity was measured at the input to the EDFA as shown in fig. 1 & fig.2. The performance of the three receiver designs at 2.5 Gbps (limited due to the bandwidth of the WC) is shown in Figure 3.

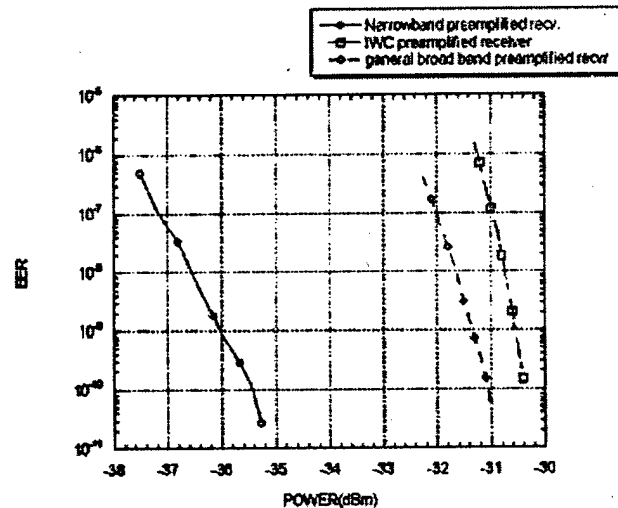


Fig. 3 BER curves for the three types of receiver designs

## 2.2 WDM All-Optical Label Swapping (AOLS) with Packet-Rate Wavelength Conversion and Subcarrier Multiplexed Addressing

We demonstrated WDM all-optical label swapping (AOLS) with wavelength conversion and subcarrier multiplexed addressing. Switching over four wavelengths covering 16 nm was demonstrated with non-inverting wavelength conversion of 2.5 Gbps payloads and burst mode recovery of tag/headers.

The AOLS architecture is shown in Figure 4. An OSCM packet transmitter modulates an RZ coded 150 Mbps header on a 16 GHz subcarrier. We demonstrated label swapping

with a NRZ coded 2.5 Gbps payload and packet duration of 1  $\mu$ s. A two-stage modified XGM/XPM SOA-WC was used to perform wavelength routing, optical tag removal and tag updating at the IP packet rate. The RF power spectrum of the incoming packet is shown in Figure 5. Wavelength conversion using XGM in an SOA efficiently transfers the baseband payload but suppresses the SCM tag as shown in Figure 5.

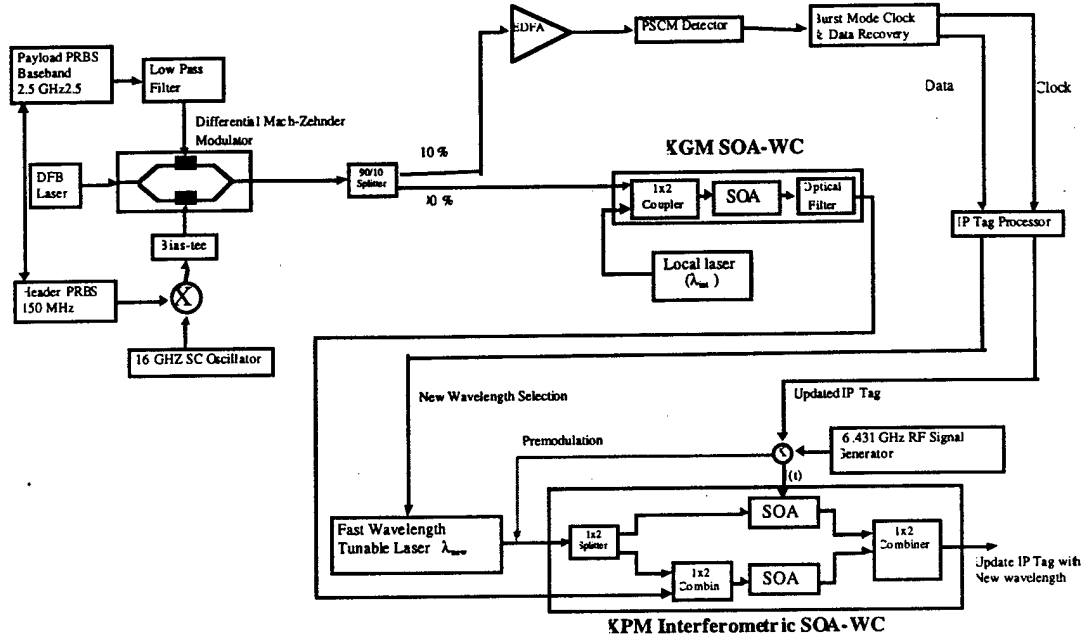


Figure 4. WDM all-optical label swapping (AOLS) experimental setup.

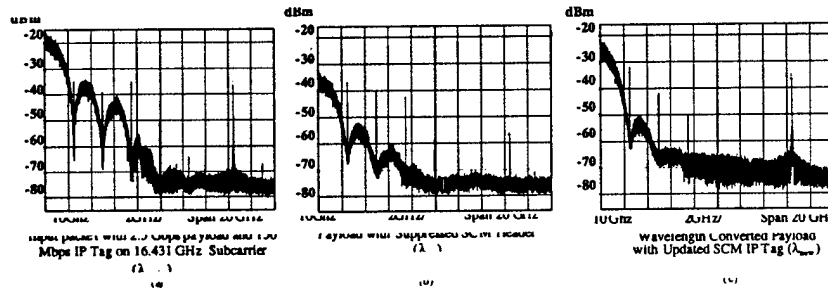


Figure 5. RF power spectrum for (a) packet input to tag switching setup, (b) output of XGM-WC showing SCM tag suppression and (c) remodulated tag after wavelength conversion.

### 2.3 Four Channel MMIC-based Transmitter Module for RF/Optical Subcarrier Multiplexed Communications

We present a compact four channel RF/optical subcarrier multiplexed (OSCM) transmitter module based on MMIC chipsets and coupled-line filters. The module generates four subcarrier signals in the 5.2 to 6GHz frequency range and supports up to 50Mbps/s data rate per channel. We present the module design and measured bit-error-rate (BER) performance of the OSCM link. This work is the first step towards fully monolithic implementation of a multi-channel OSCM transmitter module.

The transmitter module consists of 4 MMIC voltage controlled oscillators (VCO) with a frequency range of 5.2 to 6GHz for subcarrier generation, 4 MMIC FET switches for

ASK subcarrier modulation, and 4 coupled line bandpass filters to reduce interchannel crosstalk and reject baseband feedthrough. MMIC realization is critical because of the advantages over discrete components in terms of size, interconnect losses and ease of integration. The MMIC chipsets were fabricated using Triquint semiconductor TQHiP and TQTRx GaAs MESFET processes. Their performance was demonstrated with output power spectrum and BER test results using a 50Mbit/s control channel rate.

- Complete implementation of a compact four control channel OSCM transmitter module with MMICs
- Demonstration of MMIC solutions for multi-channel OSCM transmitter
- The first step in the path towards a fully monolithic implementation of a multi-channel OSCM transmitter module

The experimental module is shown in Figure 6. Performance of the four-channel transmitter module is measured with back-to-back and complete OSCM link BER tests with  $5 \times 10^{10}$  bits. All four control channel inputs are driven with a 50 Mbits/s pseudo-random bit sequence data with 2V peak-to-peak amplitude generated from three arbitrary waveform generators and BER tester. The BER is measured versus received RF power and shown in Figure 6.

### MMIC SUBCARRIER MODULE FOR PACKET LABELLING

- 4 RF Subcarriers: 5.25 GHz, 5.5 GHz, 5.75 GHz, 6GHz
- Data Rate 50 Mbps
- 9 dBm Subcarrier Output Power
- Integrated Ceramic Bandpass Filters

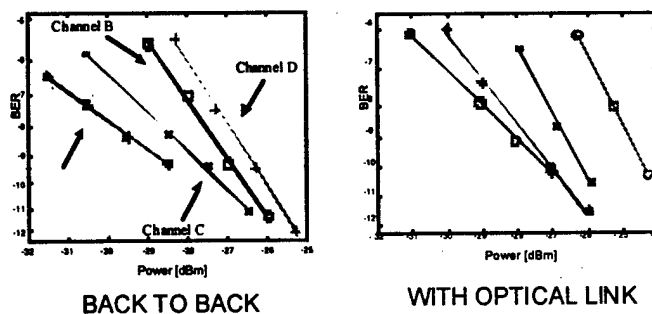
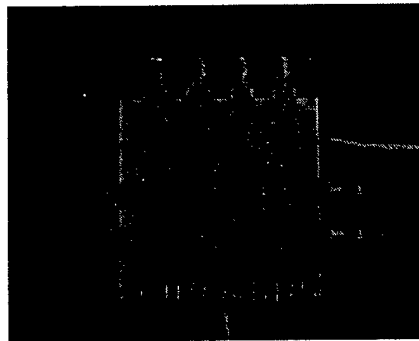


Figure 7. 4-channel MMIC subcarrier digital transceiver module and BER measurements.

## 2.4 Optical Network Channel Protection Switching Demonstration using a bi-directional Reconfigurable Multichannel Add/Drop Multiplexer

We have demonstrated channel protection switching using the bi-directional return path in an optical Wavelength Division Multiplexed ring with reconfigurable add/drop multiplexers and interleaved ITU wavelengths for the working and protection channels. The add/drop module was implemented through an acousto-optic tunable filter, while protection switching is achieved using the drop-and-continue with wavelength conversion capabilities of an optoelectronic-optical crossconnect.

The experimental setup utilized a 1.25 Gbps data lightpath (limited by the threshold circuit) on  $\lambda_1=1560.61\text{nm}$  transmitted from the right-hand side of the ring as shown in Figure 8. Channel protection switching was enabled by forward-dropping  $\lambda_1$  via the AOTF 2x2 switch. The protection switched lightpath was demultiplexed, detected and switched to  $\lambda_2=1557.37\text{nm}$  using the electronic crossbar with 2R regeneration. The protection switched lightpath was then reverse-added to the ring by the AOTF, continuing in the clockwise direction. Bit error rate (BER) measurements were made using an optical circulator as indicated in Figure 8.

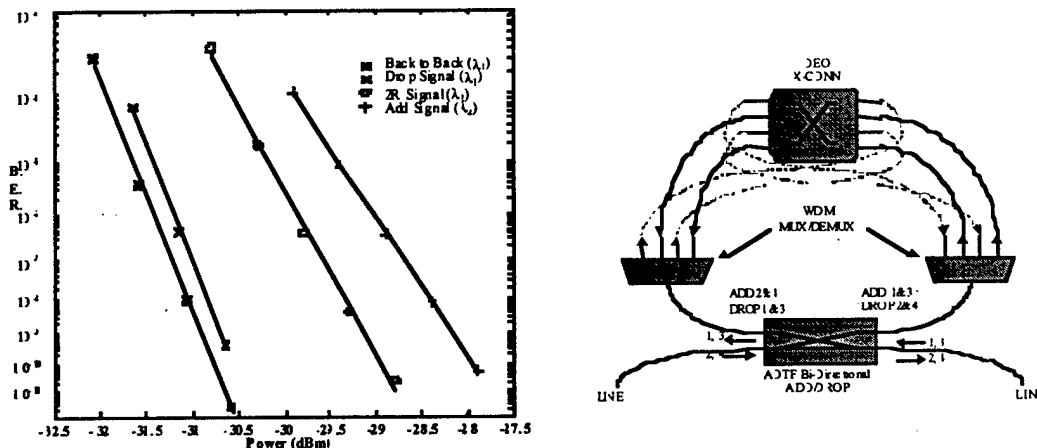


Figure 8. Results of protection switching using AOTF add/drop multiplexer.

## 3 Publications

- J1. "Remote Provisioning of a Reconfigurable WDM Multichannel Add/Drop Multiplexer," R. Guadino and D. J. Blumenthal, *IEEE Photonic Technology Letters*, Vol. 11 (8), 1060-1062, August (1999)
- J2. D. J. Blumenthal, A. Carena, L. Rau, V. Curri, and S. Humphries, "WDM Optical IP Tag Switching with Packet-Rate Wavelength Conversion and Subcarrier Multiplexed Addressing," *Technical Digest of the Optical Fiber Communication Conference (OFC '99)*, San Diego, CA, Session THM1, pp. 162-164, February 21-26 (1999).
- J3. "All-Optical Label Swapping with Wavelength Conversion for WDM-IP Networks with Subcarrier Multiplexed Addressing," D. J. Blumenthal, A. Carena, L. Rau, V. Curri, and S. Humphries, *IEEE Photonics Technology Letters*, November (1999)
- J4. F. Arecco, D. Scarano, S. Schmid, D. J. Blumenthal and R. Gaudino, "Acousto Optic Devices in Add/Drop Multiplexer Nodes," *ECOC '98*, Madrid, Spain, Vol. 1, pp. 117-118, September 20-22 (1998).
- J5. D. J. Blumenthal, A. Carena, L. Rau, V. Curri, and S. Humphries, "WDM Optical IP Tag Switching with Packet-Rate Wavelength Conversion and Subcarrier Multiplexed

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# UNIVERSITY OF CALIFORNIA, SANTA BARBARA

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SANTA BARBARA • SANTA CRUZ

DEPARTMENT OF ELECTRICAL AND  
COMPUTER ENGINEERING

SANTA BARBARA, CALIFORNIA 93106-9560

April 24, 2000

Dr. Kent L. Miller  
AFOSR/NE  
801 North Randolph Street, Room 732  
Arlington, VA 22203-1977

Dear Kent,

Please find enclosed the Final Technical Report for award F49620-98-10404,  
"Instrumentation for High Performance Highly Parallel WDM and SCM Switching,  
Processing and Communications."

Sincerely,

A handwritten signature in black ink, appearing to read 'D. Blumenthal'.

Daniel J. Blumenthal  
Associate Professor, Electrical and Computer Engineering  
Associate Director, Center for Multidisciplinary Optical Switching Technology  
University of California, Santa Barbara

cc: Lisa King  
Contract and Grant Administrator

# **Final Technical Report**

## **Research Agreement No. FA9620-98-1-0404**

**Daniel J. Blumenthal**  
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**Fax: 805-893-5705**  
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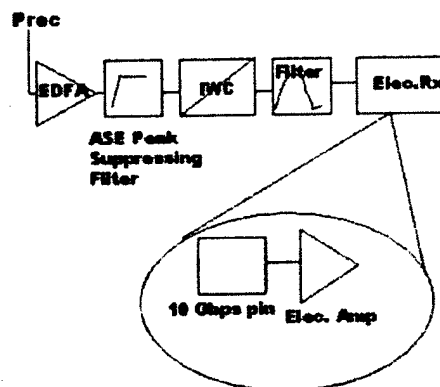


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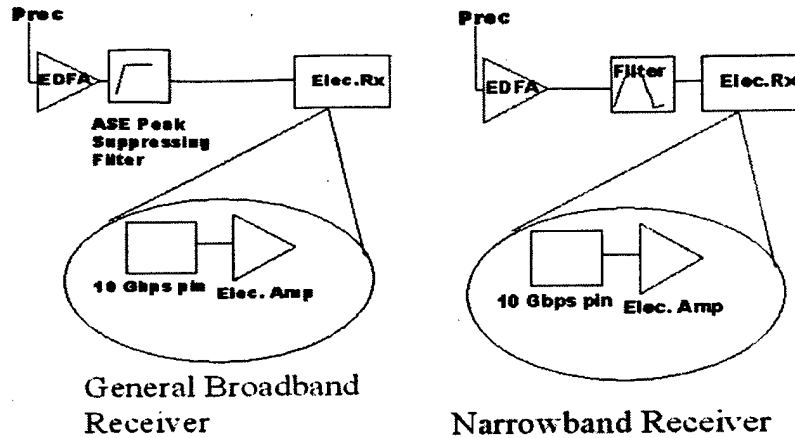


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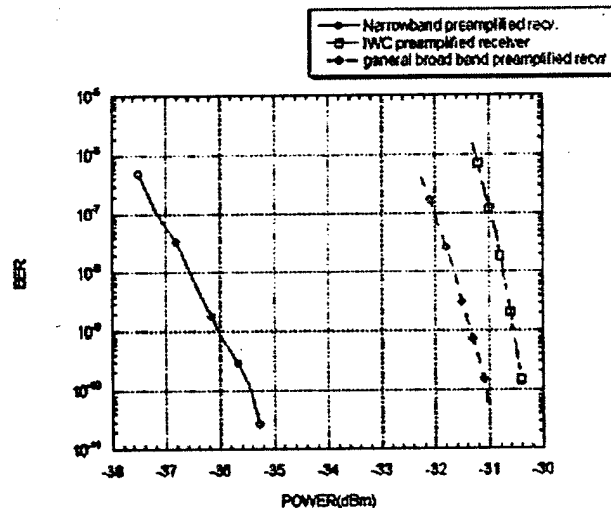


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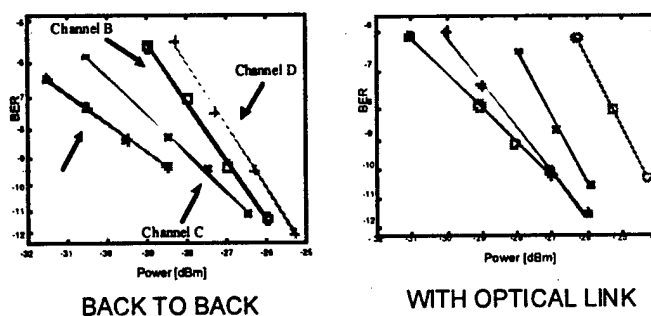
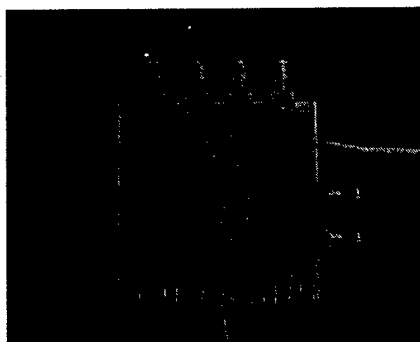


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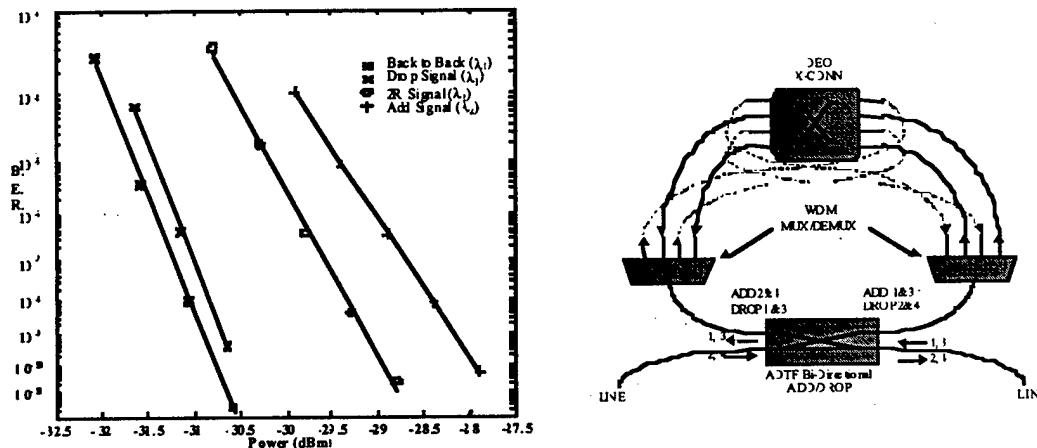


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